AFRL-SR-AR-TR-06-0085

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
12-10-2005	FINAL REPORT	01 Jan 04 THRU DEC 05

4. TITLE AND SUBTITLE

VISUAL SENSITIVITIES AND DISCRIMINATIONS

5a. CONTRACT NUMBER
F49620-03-1-0114

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
REGAN, DAVID

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
D. PHIPPS:
YORK UNIVERSITY, OFFICE OF
RESEARCH SERVICES
214 YORK LANES, 4700 KEELE ST
TORONTO, ON M3J 1P3 CANADA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

SPONSORING	MONITORING
AF OFFICE OF SCIENTIFIC RSRCH	DR. WILLARD LARKIN, PROGRAM MNGR
4015 WILSON BLVD	LIFE SCIENCES, AFOSR
RM 713, ARLINGTON, VA	801 N. RANDOLPH ST.
22203-1954, U.S.A.	ARLINGTON, VA 22203-1977 U.S.A

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

UNRESTRICTED Approve for Public Release: Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We decoupled the direction and speed of simulated self-motion in depth from the direction and speed of simulated object motion in depth. We found that objects with the same closing speed were perceived to have a higher closing speed when self-motion and object-motion were in the same direction and a lower closing speed when they were in opposite directions. In addition, the perceived direction of an approaching object's motion in depth was shifted towards the focus of the radially-expanding flow pattern caused by self-motion. These findings suggest that the large body of research on motion perception for stationary observers has limited relevance to situations in which both the observer and the object are moving. We describe evidence that the "adaptation to closing speed" effect that we reported previously causes potentially dangerous misjudgments when turning left across oncoming traffic. In particular, decisions are delayed and more variable. We have written an empirical/theoretical review of research on collision avoidance/achievement. We report evidence that practice can change the interaction between different visual variables in visually-guided action.

15. SUBJECT TERMS
TIME TO COLLISION, COLLISION AVOIDANCE, SELF MOTION; SPATIAL VISION; EVOKED POTENTIALS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			LARKIN, WILLARD
U	U	U	UU		**19b. TELEPHONE NUMBER** *(include area code)* 703-696-7793

YORK UNIVERSITÉ UNIVERSITY

VISUAL AND AUDITORY SENSITIVITIES AND DISCRIMINATIONS

AFOSR F49620-03-1- 0114

Final Performance Report 1 Jan 2004 – 31 Dec 2005

P.I. D. Regan

York University, 4700 Keele St., North York,
Ontario, Canada, M3J 1P3

TABLE OF CONTENTS

1. AIMS AND RELEVANCE

1.1 Long Term Aims

1.1.1 We will further develop the channeling hypothesis by: (a) identifying new visual channels; (b) elucidating rules for cue combination in rich visual environments; (c) advancing understanding of eye-limb coordination in skilled visual performance and the role of inter-individual variations of visual sensitivities in limiting skilled visual performance.

1.1.2 We will apply the channeling hypothesis as follows: (a) to inform the design of visual displays in flight simulators so as to improve transfer of training; (b) to provide design criteria for better interfacing night vision aids to the human user's visual system; (c) to inform the design of stereo visual displays used by operators of remotely-controlled vehicles such as unmanned air vehicles or operators of maneuverable land or sea vehicles used to inspect or repair equipment in environments hostile to life; (d) to inform the design of spatially-complex static or dynamic displays such as displays of infra-red, radar or visual imagery; (e) to design tests to screen personnel for their visual competence in specific tasks such as, for example, NOE helicopter flight, low-level aviation over snow-covered terrain, highway driving in high-glare conditions (low sun, approaching headlamps at night).

1.1.3 We will use evoked potential recording techniques to achieve the following aims: (a) identify the brain sites of different kinds of visual processing, and relate these sites to the organization of visual areas in macaque monkey cortex; (b) relate objective data on visual processing in human brain to psychophysical models of human vision.

1.2 Specific Aims

Ground–based flight simulator studies

1.2.1 I have shown mathematically that the time to collision (TTC) with an object moving directly towards the head at constant speed is given by the equation

$$\mathrm{TTC} \approx \frac{2(d\delta / dt)}{d^2\delta / dt^2} \qquad \text{----------- (1)}$$

where δ is the instantaneous relative disparity of the approaching object (Regan, 2002). We propose to find whether the human visual system contains a mechanism that is selectively sensitive to $(d^2\delta/dt^2/d\delta/dt)$ while being insensitive to $d^2\delta/dt^2$, $d\delta/dt$, and the change in disparity during a presentation ($\Delta\delta$).

1.2.2 We will measure the absolute accuracy of estimating time to passage (using binocular information only) for various oblique directions of motion in depth for stationary observer and with simulated self–motion. Equation (6) on p. 8 indicates to the pilot of a helicopter (H) flying nap–of–the–Earth the distance that a point midway between the pilot's eyes will pass wide of a distant object. The pilot needs to estimate time to passage (i.e. time to arrival level with the object) to anticipate the course change that will be needed to avoid the object . Equation (2) gives time to passage with a high accuracy.

We will repeat these experiments with both monocular and binocular information available.

1.2.3 We will measure intersubject variability in the precision and accuracy of processing $(d^2\delta/dt^2)/(d\delta/dt)$ for both a stationary observer and for simulated self–motion.

1.2.4 We will develop a quantitative mathematical (computational) model of how a moving observer estimates time to collision and time to passage with objects in the three–dimensional visual environment.

1.2.5 We will establish guidelines for the fidelity and smoothness with which the changing–disparity information about an approaching object must be displayed in a stereo flight simulator to ensure effective training in the use of binocular information in collision avoidance.

1.2.6 For an approaching object whose retinal image changes shape as it expands we will find how the accuracy of judging time to collision and time to passage is affected

by viewing distance and closing speed in the situation of simulated self–motion. (For such an object, monocular information about time to collision is either inaccurate of invalid, so judgments must be based on binocular information).

1.2.7 We will find whether simulated self–motion affects (as compared with a stationary observer) the processing of monocular and binocular information about an approaching object's direction of motion in depth. This is relevant to collision avoidance. [We had previously found a large effect of self–motion on the accuracy with which time to collision is estimated on the basis of monocular information (Gray & Regan, 2000].

1.2.8 We will compare the accuracy with which a moving observer judges time to collision with a semi–camouflaged object whose visibility is created entirely by motion contrast or entirely by texture contrast under the following conditions: on the basis of monocular information only; on the basis of binocular information only; both monocular and binocular information available. (This situation is intended to be relevant to NOE helicopter flight over undulating grassy or forested terrain). We will generate a quantitative mathematical (computational) model of observer performance.

Helicopter–borne flight simulator studies

1.2.9 We will establish whether the use of collimated optics and parallel axes in night vision goggles affects judgment of time to collision with the ground as assessed by smoothness and accuracy of landing.

Spatial vision, object perception, and seeing through camouflage

First–stage filters

1.2.10 We will find whether the human visual system contains local filters tuned to the spatial frequency and orientation of motion–defined form and, if so, will measure the filter bandwidths.

Second–stage opponent–processing

1.2.11 By comparing post adaptation thresholds for detection, and spatial frequency discrimination of motion–defined gratings we will test whether discrimination threshold is determined by the pattern of activity among first–stage spatial filters for motion–defined form, i.e. by weakly–excited filters rather than being determined, as is detection threshold, by the most strongly excited filter.

1.2.12 We will repeat the 1.2.11 protocol for cyclopean gratings.

1.2.13 We will repeat the 1.2.11 protocol for texture–defined gratings

Convergence of luminance, disparity, motion, and texture information about spatial form

1.2.14 We will establish the degree to which first–stage filters for cyclopean form, motion–defined form, texture–defined form and luminance–defined form are independent.

1.2.15 Further to 1.2.14 we will find whether these four kinds of information about spatial form have converged before the stage at which size and orientation are discriminated.

1.2.16 We will develop a qualitative mathematical (computational) model of the integration of luminance, motion, texture, and disparity information in the detection of objects and the discrimination of their spatial attributes.

Relationships between local first–stage spatial filters and long–distance fast interactions.

1.2.17 We will separate and individually characterize the early processing of information about (a) the boundaries of an object's retinal image and (b) the interior of an object's retinal image. We will generate a mathematical (computational) model of how these two kinds of information are integrated.

Brain recording studies

By providing an objective as distinct from a behavioral approach to the same questions, the following electrophysiological studies complement the psychophysical studies 1.2.10–1.2.13 on cyclopean motion–defined and texture–defined form and on the convergence of disparity, motion, luminance and texture information about spatial form (1.2.14–1.2.15).

1.2.18 We will attempt to isolate brain responses to spatial form by separating them from the brain response to the associated and simultaneous change in the visual attribute that creates the visibility of the spatial form for (a) motion–defined form, (b) cyclopean form, and (c) texture–defined form.

1.2.19 We will measure the orientation tuning bandwidth, spatial frequency tuning bandwidth, and temporal frequency tuning bandwidth of the neural mechanism sensitive to motion–defined form by recording responses from the human brain to two superimposed motion–defined gratings.

1.2.20 We will repeat 1.2.19 for texture–defined gratings.

1.2.21 We will repeat 1.2.19, but for combinations of luminance–defined, cyclopean, motion–defined, and texture–defined gratings.

1.2.22 We will develop a nonlinear multi–stage physiological model of the data obtained in Specific aim 1.2.21 using our approach described in Regan M, Regan D (1988).

2. ACCOMPLISHMENTS / NEW FINDINGS

2.1 Ground–based Simulator studies

Relevance: The relevance of this line of research is as follows: collision avoidance in both fixed–wing and rotary–wing aviation; the design of binocular and monocular flight simulators and, in particular, the effectiveness of training in collision avoidance; collision avoidance when taxiing; highway safety.

2.1 (a) Estimating the direction of motion in depth of an approaching object in the situation of simulated self–motion using a research flight simulator. Long Term Aims 1.1.1, 1.1.2. Specific Aim 1.2.2, 1.2.3, 1.2.7.

This experiment has been reported: Gray, R, Macuga, C, Regan, D. (2004). Long–range interactions between object–motion and self-motion in the perception of movement in depth. Vision Research, 44, 179–195.

In our research on collision avoidance we are investigating whether laboratory data collected for a stationary observer is valid for an observer in simulated self–motion. We had previously found that simulated self–motion had a considerable effect on judgments of time to collision with an approaching object, even though the visual information about time to collision was not affected by the simulated self motion (Gray & Regan, 2000). We have now investigated whether simulated self–motion affects the perceived direction of an approaching object's motion in depth. To anticipate, we find that there is a considerable effect when monocularly–available information only is available, but that the effect is considerably reduced when binocular (stereo) information is added.

It is well known that humans are exquisitely sensitive to visual information about an approaching object's direction of motion in depth (MID) and its time to collision (TTC). The just-noticeable difference in the direction of MID can be as low as 0.1-0.2 deg for an object approaching an observer's nose (Beverley & Regan, 1975; Portfors-Yeomans & Regan, 1997; Regan & Kaushal, 1994). For judgments of TTC, discrimination thresholds as low as 6% to 12% (Regan & Hamstra, 1993; Gray & Regan, 1998) and estimation errors for absolute TTC as low as 1.3% (Gray & Regan, 1998)* have been reported. Our ability to estimate TTC and the direction of MID is important in everyday life where we are often required to avoid or intercept an approaching object (e.g. when driving, hitting or catching).

What sources of visual information support this remarkable sensitivity? Lee, (1976) proposed that human observers estimate TTC for a rigid spherical object

---

* For the TTC values of 0.4-0.6 sec associated with professional baseball a 1.3% estimation error corresponds to a temporal error of 5.2-7.8 msec which is well within the ±9msec margin for error and is close to the 2 to 2.5 msec accuracy that can be required in cricket (Regan, Beverley, & Cynader, 1979).

directly approaching the eye at a constant speed on the basis of the following equation derived by Hoyle (1957)

$$TTC \approx \theta/(d\theta/dt) \qquad \text{-----------} (1)$$

where θ is the approaching object's instantaneous angular subtense, and θ is small. Some of the early research based on Lee's proposal has been severely criticized by Wann (1996). For example, in many early studies the participants viewed the approaching object with both eyes, and it has recently been shown theoretically that binocular information about TTC is available. In particular

$$TTC \approx I/D(d\delta/dt) \qquad \text{-----------} (2)$$

for an object directly approaching an observer's head, where I is the interpupillary separation, $d\delta/dt$ is the rate of change of relative disparity, and D>>I (Regan, 1995). In addition

$$TTC \approx 2(d\delta/dt)/(d^2\delta/dt^2) \qquad \text{-----------} (3)$$

(Regan, 2002), an equation that does not involve distance. Furthermore, it has recently been shown empirically that normally–sighted observers are able to use binocular information about TTC either by itself or in combination with the information expressed in equation (1) (Gray & Regan, 1998). However, the question of how information about TTC are combined for different perceptual-motor tasks is still incompletely understood.

As to the direction of an approaching object, again both monocular and binocular visual correlates are available. One monocular correlate of the direction of motion of an approaching rigid sphere of diameter s is expressed in equation (4) (Bootsma, 1991; Regan, 1986; Regan & Beverley, 1980; Regan & Kaushal, 1994)

$$n \approx 2(d\phi/dt)/\ (d\theta/dt) \qquad \text{-----------} (4)$$

where ns is the distance by which the centre of the sphere will miss the centre of the eye, s is the radius of the sphere, $d\phi/dt$ is the angular velocity and $d\theta/dt$ the rate of expansion of the sphere's retinal image. Turning to binocular information, the ratio between the angular velocities of the approaching object's images in the two eyes is a correlate of the direction of motion in depth, though only for motion within the plane containing the object and the two eyes (Beverley & Regan, 1973). Equation (5), however, expresses a binocular correlate for motion within any meridian.

$$\beta \approx \tan^{-1}[I(d\alpha/dt)/D(d\delta/dt)] \qquad \text{----------- (5)}$$

where β is the direction of motion relative to a line from the approaching object to a point midway between the eyes, D is the viewing distance, I is the interpupillary separation, $d\alpha/dt$ is the angular velocity of the object's binocularly–fused image, $d\delta/dt$ is the rate of change of relative disparity, D>>I, and the object is straight ahead (Regan, 1993). Equation (5) can be rewritten in the form

$$L \approx I(d\alpha/dt)/(d\delta/dt) \qquad \text{----------- (6)}$$

Where L is the distance between a point midway between the eyes, and the location of the approaching object at the instant it passes the head (Regan et al., 1995).

Previous research on the perception of MID has been mostly restricted to the case of stationary observer and moving object (reviewed in Regan and Gray, 2000). Because equations (1)–(6) are equally valid for the case of stationary observer/moving object, moving observer/stationary object, or any combination of the two, on the face of it one would not expect self–motion to affect either judgments of TTC or judgments of the direction of an approaching object's MID. Therefore, it might seem safe to assume that the results of laboratory experiments performed with a stationary observer would be valid in the everyday situation that a moving observer must judge an approaching object's direction of MID and its TTC. This however seems not to be the case.

When an observer moves forward through a three–dimensional visual environment a radially–expanding flow pattern is created on the retina, In a recent experiment the observer was stationary but the presence of the radial flow pattern created an illusion of self–motion (Gray & Regan, 2000b). We found that this radial flow pattern substantially altered TTC estimates based on monocular information alone (i.e., equation 1) for a foveated approaching object. In particular, simulated forward self-motion shortened the perceived TTC by 10-13% and simulated backward self-motion lengthened perceived TTC by 17-23%. The key feature of this study was that our procedure allowed us to decouple simulated object-motion from simulated self-motion, i.e. that the peripheral flow field did not affect the value of $\theta/(d\theta/dt)$ for the approaching object.

The purpose of the study reported here was to further examine the interaction between simulated self-motion and the perceived speed and direction of motion of simulated object moving in depth. This was achieved by superimposing a simulated approaching object on a large-angle radial flow field. As was the case in our earlier study, the flow field and simulated approaching object were controlled independently. In Expt. 1, we investigated the interaction between the speed of simulated self-motion and the perceived speed of object MID. In Expt. 2, we examined the interaction between the direction of self-motion and the perceived direction of object MID. In Expts. 3 & 4, we investigated whether the addition of binocular information about the motion of the approaching object altered these interactions.

Experiment 1

In a preliminary Expt. we asked which optic variable(s) are used to estimate the speed of MID for a receding object. In the main Expt. we examined the effect of a radial flow pattern (i.e. simulated self-motion) on speed discrimination.. To expand on our previous TTC study, in the present experiment we simulated (i) approaching and receding objects combined with simulated forward and backwards self-motion and (ii) interleaved different ratios of object-motion speed to self-motion speed. In Expt.1 only monocular information about motion in depth was available, as was the case in our previous study (Gray & Regan, 2000b).

We simulated constant velocity self–motion in a straight line through a cloud of randomly–positioned stationary objects (i.e. radial optic flow). A flow pattern consisting of small white squares was back–projected (Mitsubishi model #LVP-X7OU) onto a large (65° horizontal x 88° vertical) screen. The viewing distance was 1m. In the main Expt., to simulate forward motion, the flow elements increased speed and grew larger as they moved radially outward from the focus*. The backward (contracting) flow pattern was the reverse. The speed of simulated self-motion was varied as described below. Results obtained with these two types of simulated self-motion were compared with those obtained using a "static" condition in which all flow elements remained stationary.

---

* We found previously that the effect of a flow field on estimates of TTC was considerably less when the flow elements remained constant in size as they moved outwards (Gray & Regan, 2000b)

A target square was presented at the center of the flow pattern. The square was purple and was easily distinguishable from the flow elements. A sensation of approaching (or receding) object motion in depth was created by increasing (or decreasing) the size of this object square according to the equation that relates object subtense to time (Regan & Hamstra, 1993). As shown in Fig. 1, no flow elements were presented in a central square region of the display. The side length of this square hole was varied as described below.

In the preliminary Expt. the reference target on all trials simulated an approaching object with a value of $(d\theta/dt)/\theta$ equal to $0.54\ s^{-1}$. The test was receding on all trials and had a speed of MID that was chosen randomly from one of eight values of $(d\theta/dt)/\theta$: -0.43, -0.47, -0.5, -0.52, -0.55, -0.59, -0.63, $-0.73\ s^{-1}$. The starting size of the target was varied as described for Expt.1. The flow field was static for both the test and reference targets.

Psychometric functions for discriminating trial–to–trial variations in the speed of object MID were measured using the method of constant stimuli combined with two–interval forced choice. We first describe the procedure for simulated approaching objects. Each trial consisted of two presentations of a simulated approaching object: a "reference presentation" and a "test presentation". It has been proposed that the perceived closing speed of MID for approaching objects is inversely proportional to the object's TTC (Regan & Hamstra, 1993). Therefore we expressed the speed of object MID in terms of the value of $(d\theta/dt)/\theta$ *. In the "reference presentation" the flow elements remained stationary and the perceived speed of object MID [expressed as the value of $(d\theta/dt)/\theta$] was proportional to the mean of the stimulus set ($0.54s^{-1}$). In the "test presentation", either forward or backward self-motion was simulated and the speed of object MID was chosen randomly from one of eight values (0.43, 0.47, 0.5, 0.52, 0.55, 0.59, 0.63, $0.73s^{-1}$). During this presentation the perceived speed of simulated self-motion (i.e. the rate of

---

* According to dimensional theory, the dimensions of both sides of an equation must match (Szirtes, 1998). Since speed has the dimensionality (length/time) and $(d\theta/dt)/\theta$ has the dimensionality (time-1), the constant of proportionality must have the dimensionality (length).

radial flow) depended on the ratio between self-motion and object-motion*. Eight ratios (0.5, 1.0, 1.5, 2.0, -0.5, -1.0, -1.5 and -2.0) were used and the value was varied randomly from trial-to-trial. Negative ratios indicate conditions where the direction of object-MID and self-MID were opposite. The observer's task was to indicate, by pressing one of two response keys, in which presentation the object was moving faster. The order of the two presentations was chosen randomly and the duration of each presentation was 450 msec.

In order to determine whether observers based their responses on the task-relevant variable [$(d\theta/dt)/\theta$] as opposed to any of the task-irrelevant variables (e.g., the rate of expansion $d\theta/dt$)†, the values of initial $(d\theta/dt)/\theta$ and $d\theta/dt$ were varied orthogonally in an 8X8 stimulus array by varying the starting size (i.e. at time t=0) of the simulated approaching square. (See Regan and Hamstra (1993) for a further description of this procedure). The starting size ranged between 0.4 deg and 1.2 deg for the approaching target.

A similar procedure was used to measure speed discrimination performance for receding targets. Previous research has not clearly identified the optical variables used to estimate perceived speed for receding objects. Described below is a formal test of whether it is also determined by the value of $(d\theta/dt)/\theta$. For receding targets, "the reference presentation" consisted of a static flow pattern and an object-MID speed of –0.54 (the mean of the stimulus set). In the "test presentation", either forward or backward self-motion was again simulated and the speed of object MID was chosen randomly from

---

* The ratio between the speed of object MID and the speed of self-MID was equal to $K\frac{(d\theta/dt)_{t=0}}{d\alpha/dt}$ where $(d\theta/dt)_{t=0}$ was the object's rate of expansion at time t=0 and $d\alpha/dt$ was the angular velocity of the flow pattern (measured from the focus of expansion) and K was a constant. See Fig. 1. In the everyday world, constant K would depend on the distances of the various external objects represented by the individual squares in the flow pattern. However, since we studied the effect of different scaling factors, each of which was applied to the local velocity over the entire flow pattern, the value of K is irrelevant to our conclusions and for convenience we set it at unity.

† In a separate control experiment we varied the presentation duration between 450-900msec to remove the total change in size $\Delta\theta$ as a reliable cue to the speed discrimination task. The results from this control experiment we similar to those in Expt. 1.

one of eight values (-0.43, -0.47, -0.5, -0.52, -0.55, -0.59, -0.63, -0.73). We randomly interleaved the same 8 self-MID speed/object-MID speed ratios as described for the approaching object. The starting size ranged from 1.5 deg to 4.5 deg for the receding target.

Each run consisted of 512 trials comprised of 64 moving objects X 4 self-motion/object-motion ratios X 2 directions of self-motion (forward and backwards). Psychometric functions for receding and approaching object MID were measured on separate runs. Across runs we also varied the side length of the square hole with no flow elements (see Fig.1). Five side lengths were used (9, 11, 13, 18 and 26 deg) and the order was counterbalanced.

Five observers completed Expt. 1. Observer 1 and 2 were authors R.G. and K.M. respectively. Observers 3-5 were naive as to the aims of the study and completed the experiments for partial course credit.

Results

Which optic variables determine perceived speed for receding motion?

Variable $(d\theta/dt)/\theta$ explained the most response variance (R^2 ranged from 0.69 to 0.88). The rate of size change explained a small (but significant) amount of additional variance for two of the observers (additional R^2 ranged from 0.05 to 0.11). We conclude that perceived speed for receding MID is predominantly determined by the variable $(d\theta/dt)/\theta$.

Effect of the direction of self-motion on the perceived speed of object MID

Fig. 2A & B shows respectively the psychometric functions for approaching and receding objects for observer 1. These particular functions are for a hole-size of 9 deg and self-motion/object-motion speed ratios of either 1.0 or –1.0 (see figure legends). These psychometric functions were submitted to probit analysis (Finney, 1971) and the resulting curve fits are shown in Fig. 2. It is clear that the direction of simulated self-motion had a substantial effect on the perceived speed of object MID. Even though the peripheral flow field did not alter the value of $(d\theta/dt)/\theta$ for the moving object, objects

moving in depth were perceived to be moving faster (i.e., there was greater percentage of "test faster" responses) relative to the reference target when the direction of object motion was the same as the direction of self-motion and were perceived to be moving more slowly (i.e., lower percentage of "test faster" responses) relative to the reference target when the direction of self-motion and object-motion were opposite.

To quantify these effects we calculated the point of subjective equality (i.e., the 50% point) for the psychometric functions. Fig. 3A & B shows the points of subjective equality (PSE) for approaching and receding objects for the 5 observers. For all observers, objects were perceived to be moving faster (lower PSE) when the direction of object motion was the same as the direction of self-motion (a ratio of 1.0 in Fig.3) and were perceived to be moving more slowly (higher PSE) when the direction of self-motion and object-motion were opposite (a ratio of -1.0 in Fig.3). Paired t-tests revealed the PSE was significantly smaller for simulated forwards self-motion than backwards self-motion when the object was approaching [$t(4)=8.2$, $p<0.001$] and that the PSE was significantly larger for simulated forwards self-motion than backwards self-motion when the object was receding [$t(4)=9.2$, $p<0.001$]. Further statistical analyses of these effects are described below.

From Fig.3 it can be seen that for some conditions the shifts in perceived speed were roughly symmetrical about the speed of the reference target. However some observers did show large overall biases in speed perception. In particular, observer 4 in Fig. 3A and observer 5 in Fig. 3B showed a tendency to perceive all test targets as moving faster than the mean. Overall paired t-tests revealed no significant differences between the mean PSE (i.e., averaged over both directions of self-motion) and the speed of the reference target: Fig.2A: $t(4)=-0.4$, $p>0.5$; Fig.2B: $t(4)=0.2$, $p>0.5$. Biases in speed perception are discussed in further detail below.

Speed discrimination thresholds were similar for all combinations of object-motion and self-motion. Discrimination thresholds were defined as $0.5*(S_{75}-S_{25})$ where S_{75} and S_{25} were respectively the object-MID speeds for 75% and 25% "test target faster than the reference" responses. For the approaching target, thresholds ranged between 4% and 28% for forwards self-motion and the mean threshold was 12% (SE=3%). For backwards self-motion, thresholds ranged between 9% and 25% and the mean threshold

was 15% (SE=3%). The difference between means was not statistically significant [t(4)=0.6, p>0.5]. For the receding targets, thresholds ranged between 6% and 21% for forwards self-motion and the mean threshold for forwards self-motion was 14% (SE=3%). For backwards self-motion, thresholds ranged between and 6% and 27% and the mean threshold was 14% (SE=4%). The difference between means was not statistically significant [t(4)=0.3, p>0.5].

Effect of the self-motion/object-motion speed ratio on the perceived speed of object motion in depth

Fig. 4A shows the points of subjective equality (PSE) for the 8 different self-motion/object-motion speed ratios for observer 1. These data are for the approaching object. Increasing this ratio appeared to have two main qualitative effects on the perceived speed of object MID: (i) there was an increase in perceived speed for both directions of self-motion, and (ii) the absolute difference between PSE's for the two directions of self-motion decreased until the effect reversed for the highest ratios. Similar patterns of data were obtained for the other 4 observers.

Quantitative analyses were consistent with these informal observations. We first performed a 2X4 repeated measures ANOVA with Self-Motion Direction and Ratio as conditions. This analysis revealed significant main effects of Ratio [F(3,12)=23.8, p<0.001] and of Self-Motion Direction [F(1,4)=50.6, p<0.001] . Post-hoc trend analysis revealed a significant linear trend [F(1,12)=138, p<0.001] for Ratio. Finally, a paired t-test revealed that the difference between the PSE for forwards self-motion and backwards self-motion was significantly greater for the ratio of 1.0 than it was for the ratio of 2.0 [t(4)=6.1, p<0.001].

The self-motion/object-motion speed ratio did not affect speed discrimination thresholds for the approaching target. A 2X4 repeated measures ANOVA performed on thresholds revealed non-significant main effects of ratio [F(3,12)=0.51, p>0.5] and self-motion direction [F(1,4)=5.1, p>0.1]. The ratio X direction interaction was also not statistically significant [F(3,12)=4.0, p>0.05].

Fig. 4B shows the points of subjective equality (PSE) for the 8 different self-motion/object-motion speed ratios for observer 1. These data are for the receding object.

Varying the ratio produced the same effects as those described for the approaching target, i.e. an overall increase in perceived speed and a decrease in the effect of motion direction. The quantitative analyses were again consistent with the informal observations: significant main effects of Ratio [$F(3,12)=30.1$, $p<0.001$] and of self-motion direction [$F(1,4)=44.2$, $p<0.001$] .

As was the case for the approaching target, the self-motion/object-motion speed ratio did not affect the speed discrimination thresholds for the receding target. Significant results of the ANOVA were: ratio [$F(3,12)=19.5$, $p>0.001$] and direction [$F(1,4)=33.2$, $p>0.001$].

Effect of the central hole size on the perceived speed of object MID

Fig. 5A shows the points of subjective equality (PSE) for the 5 different central hole-sizes for observer 1. These data are for the approaching object. Increasing the size of the central hole appeared to reduce the effect of self-motion direction on the PSE's without causing any overall bias in perceived speed. Hole size data for the 5 observers were analyzed using a 5X2 repeated measures ANOVA with hole size and self-motion direction as factors. This analysis revealed a significant main effect of direction [$F(1,4)=15.4$, $p<0.05$] and a significant direction X hole size interaction [$F(4,16)=6.2$, $p<0.01$]. The main effect of hole-size was not significant. Post-hoc interaction contrasts (Keppel, 1991) revealed that the effect of direction was significantly greater at hole size 9 deg than it was at a hole size 26 deg [$F(1,16)=4.6$, $p<0.05$]. There was no significant difference between the effect of direction for the 9 and 18 deg hole sizes [$F(1,16)=2.3$, $p>0.05$].

Similar results were obtained for receding objects. Fig. 5B shows the PSE's for the 5 different central hole-sizes for observer 1. Significant results of the ANOVA were as follow: significant main effect of direction [$F(1,4)=10.3$, $p<0.05$]; significant direction X hole-size interaction [$F(4,16)=5.3$, $p<0.05$]; significant interaction contrast between hole sizes of 9 and 26 deg [$F(1,16)=5.2$, $p<0.05$]. There was no significant difference between hole sizes of 9 and 18 deg [$F(1,16)=0.2$, $p>0.05$].

The central hole size did not affect the speed discrimination thresholds for either the approaching or receding target. A 5X2 repeated measures ANOVA with hole size and self-motion direction as factors revealed no significant effects.

Stepwise regression analyses

To determine whether observers based their responses on the task-relevant variable we submitted the data to a forward stepwise regression analysis. For all 5 observers the task-relevant variable $(d\theta/dt)/\theta$ accounted for a high proportion of total variance (R^2 ranged from 0.7 to 0.94) across conditions.

Discussion

The direction of simulated self-motion had a substantial effect on the perceived speed of object MID. When the perceived speed of object MID and self-motion was equal, simulated forward self-motion increased the perceived speed of object MID by 5% to 12% and simulated backward self-motion decreased perceived speed by 3% to 10%. Qualitatively these effects are similar to results we reported for judgments of TTC (Gray & Regan, 2000b), however the effect of backwards self-motion on perceived speed (6% shift on average) in the present study was considerably smaller than the effect we reported previously (19% average shift). One likely explanation for this difference is that in our previous experiment we used a constant speed of self-motion and varied the TTC of the approaching object according to a staircase tracking procedure, so that the ratio between the speed of self–motion and the object's TTC varied randomly from trial-to-trial. As discussed next, this ratio appears to have a large influence on the interaction between self-motion and object motion.

Increasing the ratio between the speed of simulated self–motion and the speed of object-motion resulted in a qualitatively different type of interaction between the two types of motion. The substantial effect of the direction of self-MID that was observed for small ratios saturated at larger ratios. The simulated self-motion created an increase in perceived speed for <u>all</u> combinations of the direction of self-MID and the direction of object MID. This resulted in a complete reversal of the effect for backwards self-motion in Fig.3A and for forwards self-motion in Fig.3B. It should be emphasized that this

dramatic change in overall speed perception occurred even though speed discrimination thresholds were unchanged and observers continued to base their responses on the task-relevant variable. Thus the effect of ratio we observed cannot be explained by a change in the strategy used to perform the task (e.g., basing the speed judgment on the rate of optic flow).

The effect of the direction of self-MID on the perceived speed of object MID (for a ratio of 1.0) extended over a large distance relative to the 1.5 deg to 2.0 deg receptive field diameter of a changing-size detectors (Regan & Beverley, 1979). A significant effect was observed even when we introduced an 8 deg gap (i.e., 18 deg hole size) between the outer edge of the object and the inner edge of the peripheral flow pattern.

In the main Expt. our observers based their responses on the optical variable $(d\theta/dt)/\theta$ for all stimulus conditions. This finding is important for two reasons. Firstly, it is strong support for the proposal that the perceived speed of object MID is inversely proportional to the object's TTC (Regan & Hamstra, 1993). Secondly, it further supports our proposal that the interaction between simulated self-MID and object-MID occurs at the stage when the motion-in-depth signal is generated rather than at the stage where changing image size is processed (Gray & Regan, 2000b). If this interaction occurred at the level of changing-size detectors we might expect the simulated self-motion to alter the value of $d\theta/dt$ for the approaching object that would be evidenced by observers' placing more weight on this particular variable.

Experiment 2

In Expt.1 we found substantial interactions between the speed of simulated self-motion (i.e. the radial flow pattern) and the perceived speed of object-motion. In Expt. 2 we asked whether there are interactions for perceived judgments of direction? Previous research has focused on the influence of object motion on judgments of the direction of self-motion i.e. heading (Royden & Hildreth, 1996, Warren & Saunders, 1995), but the converse relationship has not previously been explored. In Expt.2 we measured the discrimination of the direction of object MID as a function of the direction of simulated self-motion.

The apparatus was as described in Expt.1 except for the following. The location of the focus of expansion (FOE) of the flow pattern was varied from trial to trial to simulate different directions of self-motion. As shown in Fig.6, there were three different FOE locations: (a) 7 deg left of the center of the display (-7 deg), (b) center of the display (0 deg) and (c) 7 deg right of the center of the display (+7deg). Only the forward self-motion and static conditions were used in Expt.2. The radial velocity of the flow pattern for the forward condition was varied randomly between 5 and 10 deg/sec. As was the case in Expt.1., no flow elements were presented in a central square region of the display so that the simulated object never overlapped the flow elements. Therefore, the flow field did not alter the ratio between the rate of expansion of the approaching object and its angular speed within a frontoparallel plane, i.e. its direction of MID, see equation (4).

Psychometric functions for discrimination of the direction of the object's motion were measured using the method of constant stimuli combined with two interval forced choice. Each trial consisted of two intervals, in each of which an approaching object was simulated. In the reference interval, the flow elements remained stationary* and the direction of object MID was the mean of the stimulus set (12.1 deg leftward of the midline). In the test interval, forward self-motion was simulated and the location of the FOE was chosen randomly from the three locations shown above. For this interval the object MID direction was chosen randomly from one of eight values (0.6, 4, 8.5, 11.3, 14, 16.7, 17.7 and 23.7 deg leftward of the midline). The order of the two intervals was chosen randomly and the duration of each interval was 500 msec. The observer's task was to signal in which interval the simulated approaching object appeared to be moving more leftward by pressing one of two response keys.

In order to check that observers based their responses on the direction of the approaching object rather than task–irrelevant variables such as frontal-plane speed or the rate of expansion, we used the triple dissociation technique developed by Portfors-Yeomans and Regan (1997). In this technique, stimuli are divided into an array where

* In all reference intervals the layout of the flow elements was identical to the initial position of the elements for the corresponding test interval for that trial. So, for example, when the test interval had an FOE of –7deg the reference flow pattern would be as shown in Fig. 6A and when the test interval had an FOE of +7deg the reference flow pattern would be as shown in Fig. 6C.

the MID direction is varied along one axis of the array and frontal plane speed is varied along the other axis of the array. The rate of expansion is varied in the same way along both axes of the array (see Fig. 3 in Portfors-Yeomans and Regan (1997) for further details). In the present study each run consisted of 192 trials comprised of 64 approaching objects (8X8 array) X 3 directions of self-motion (i.e., FOE locations). Across runs we also varied the side length of the square hole with no flow elements using the 5 values used in Expt.1. We also collected data for a condition where the flow elements remained static for both the test and reference presentations.

Four observers completed Expt. 2. Observer 1 and 2 were authors R.G. and K.M. respectively. Observers 6 and 7, who were naïve to the aims of the study, completed the experiments for partial course credit.

Results

Effect of the direction of self-motion on the perceived direction of object MID

Fig. 7 plots psychometric functions for the smallest central hole size (9 deg) for observer 1. The solid arrow indicates the direction of object MID for the reference interval (i.e. the mean of the stimulus set). It is clear from Fig.7 that the location of the FOE had a systematic effect on the perceived direction of object MID. For simulated self-motion with a heading 7 deg to the left of the midline (i.e., Fig.6A), this observer perceived the object's trajectory to be shifted roughly 3 deg leftward. Conversely, for simulated self-motion with a heading 7 deg to the right of the midline (i.e., Fig.6B), this observer perceived the object's trajectory to be shifted roughly 3 deg rightward. Similar results were obtained for the other 3 observers. Fig.8 plots the PSE's for the three FOE locations for all 4 observers. Paired t-tests revealed significant differences between PSE(-7deg) vs. PSE(0 deg) [$t(3)=8.4$, $p<0.001$] and between PSE(+7deg) vs. PSE(0 deg) [$t(3)=5.6$, $p<0.001$]. The effect of self-motion direction on discrimination thresholds is described below.

Effect of the central hole-size on the perceived direction of object MID

Fig. 9A plots the difference between the PSE for the –7deg FOE location and the PSE for the +7deg FOE location for the five central hole sizes. Data are again for

observer 1. The "Static" data show the PSE difference for the condition in which the flow elements were static for both the test and reference intervals. The effect of simulated self-motion on the perceived direction of object MID decreased as the size of the central hole in the flow pattern was increased. Data were similar for the other 3 observers. To analyze the effect of hole size we performed a 3X5 repeated measures ANOVA with FOE location and hole size as factors. There was a significant main effect of FOE location [$F(2,6)=6.5$, $p<0.05$] and a significant FOE location X hole size interaction [$F(8,24)=4.1$, $p<0.01$]. Post-hoc interaction contrasts (Keppel, 1991) revealed that the effect of direction was significantly greater at hole size 9 deg than it was at a hole size 26 deg [$F(1,24)=5.8$, $p<0.05$]. There was no significant difference between the effect of direction for the 9 and 18 deg hole sizes [$F(1,24)=0.3$, $p>0.5$].

A second effect can be seen in Fig.9B. This Fig. plots the PSE values for the FOE of 0 deg (i.e., self-motion straight ahead) for the 4 observers. The "Static" data are for the condition in which the flow elements remained stationary in both the test and reference intervals. It is clear from this Fig. that our observer had a "self-motion collision bias". That is, the perceived direction of object MID during forward self-motion was shifted towards the nose (i.e. closer to a PSE equal to 0.0) relative to the static condition. Paired t-tests revealed that this difference was statistically significant [$t(3)=6.8$, $p<0.001$].

Finally, we found that simulated self-motion degraded an observer's ability to discriminate the direction of MID. Fig. 10 plots mean discrimination thresholds (collapsed across all FOE locations) for observer 1. When the hole size was less than roughly 17 deg, the mean discrimination threshold for the 'static' condition was lower than for simulated forward self-motion. Similar results were obtained for the other 3 observers. To analyze this effect we performed a 3X5 repeated measures ANOVA on the discrimination thresholds data with FOE location and hole size as factors. There was a significant main effect of hole size [$F(4,12)=6.6$, $p<0.01$]. The main effect of FOE location and the location X hole size interaction were not significant.

Stepwise regression analyses

To determine whether observers based their responses on the task-relevant variable we submitted the data collected in Expt.2 to a forward stepwise regression

analysis. For all 5 observers the task-relevant variable (i.e., equation 3) accounted for a high proportion of total variance (R^2 ranged from 0.75 to 0.89) across conditions.

Discussion

In the everyday world the ratio of an object's rate of expansion to its rate of lateral motion (i.e., equation 4) provides reliable information about the direction of MID regardless of whether the approach is produced by self-motion, object-motion or a combination of both. Despite this fact, our observers appear to combine self-motion and object-motion information when judging the direction of object MID. Simulated forward self-motion to a point 7 deg left of the midline shifted the perceived direction of object MID leftwards (by 2.9 deg on average) and simulated forward self-motion to a point 7 deg right of the midline shifted the perceived direction of object MID rightwards (by 3.2 deg on average). This significant interaction between self-motion object-motion was not abolished until the gap between the outer edge of the object and inner edge of the flow patter was greater than roughly 9 deg. This range is similar to that found for perceived speed judgments in Expt. 1.

It should be emphasized that, as was the case for the perceived speed and TTC findings, these shifts in perceived direction cannot be caused solely by a change in the relative motion between the object and the surrounding flow elements , because the shifts in perceived direction were in the same direction as the simulated self-motion. Instead we propose that it provides further evidence that motion-in-depth signal generated by local changing size detectors that process object motion is being combined (in a weighted sum) with the motion-in-depth signal generated by the flow pattern.

Simulated self-MID degraded our observers' ability to discriminate the direction of object MID. Direction discrimination thresholds during forwards self-motion were 37% to 62% higher (on average) than thresholds for a static flow-field. This is surprising given that self-motion did not affect discrimination thresholds for the speed of object MID and also because there are many situations in the everyday world where we need to judge accurately the direction of object MID while we are moving, for example when overtaking a vehicle on the highway. Our finding may be related to the report of Probst, Brandt & Degner (1986) who found that thresholds for lateral motion increased by a

factor of 5.5 during concomitant forwards self-motion and increased by a factor of 18 during concomitant lateral self-motion.

Relative to the static condition the perceived trajectory of object MID (as indexed by the PSE) was biased towards the observer's midline during simulated self-motion, even though visual cues to object MID were the same in both conditions. Furthermore, all observers reported that, "the object would have collided with my head when more frequently when I was moving forward then when I was stationary". This bias may provide a "safety first" ecological advantage.

Experiment 3

Expts. 1 and 2 we considered only monocular cues to speed and direction. In Expt. 3 we ask whether the addition of binocular information about TTC and direction of MID reduces the judgment errors caused by self-motion. Our rationale is based on the finding that, for large objects, absolute estimates of TTC are more accurate when binocular information is available (Gray & Regan, 1998). Furthermore, the addition of binocular information permits accurate estimates of TTC in situations where TTC cannot be estimated accurately on the basis of monocular information alone [e.g. for small objects (Gray & Regan, 1998) and for rotating nonspherical object (Gray & Regan, 2000a).

A flow pattern consisting of small white squares was displayed on an SVGA computer monitor that subtended 38° horizontal x 27° vertical. The viewing distance was 57 cm. A smaller display and closer viewing distance were used in Expt. 3 because they permitted a better quality stereo image than the LCD projector used in Expts. 1 & 2. The impact of these changes is discussed further below. The peripheral flow pattern was the same as described for Expts.1 & 2. In all conditions of Expt. 3 the elements of the flow pattern all had zero retinal disparity.

As was the case in Expts.1 & 2, a simulated approaching square was presented at the center of the flow pattern. In Expt.3. the central hole size was held constant at 9 deg. The simulated approaching motion in depth was created by increasing the angular size of the object and/or by increasing its relative retinal disparity. The disparity of the object was varied according to the equation:

$$\delta_t = \delta_0 + \frac{It}{D_0 TTC(1 - t/_{TTC})} \qquad \text{----------- (6)}$$

where δ is the retinal disparity relative to a fixed reference point and D_0 is the viewing distance (see Gray and Regan (1998) for further details). Only approaching objects were simulated in Expt.3.

Psychometric functions for speed discrimination were measured as described for Expt. 1. The MID cues available to the observer were varied across runs. Each observer completed the following 3 conditions: (1) monocular information alone; (2) binocular information alone; (3) both monocular and binocular information signaled the same TTC.

In order to check that observers based their responses on task–relevant variables we used an 8x8 stimulus array. Within the array the values of initial [I/D $(d\delta/dt)$] and $\Delta\delta$ (i.e. the total change in disparity within a trial) were varied orthogonally by varying the presentation duration (Δt) by ±40% about a mean value of 500 msec (see Gray & Regan (1998) for further details). Each run consisted of 128 trials comprised of 64 approaching objects X 2 directions of self-motion (forward vs. backwards). Psychometric functions for different object MID cues were measured on separate runs and the order was counterbalanced

Observers 1, 3, 4 and 5 completed Expt. 3.

Results

Monocular Information Alone

We replicated Expt. 1 using the Expt. 3 apparatus described above. The % difference in PSE values between forwards and backwards self-motion were as follows: Observer 1: 7.2%, Observer 3: 9.9% Observer 4: 5.3% and Observer 5: 12%. A paired t-test revealed that these differences were not significantly different for the two experimental setups [t(4)=1.2, p>0.5].

Binocular Information Alone

Fig. 11A shows the psychometric functions for the condition in which object MID was produced by binocular information alone (i.e., equations 2 and 3). Data are for observer 1. The most striking aspect of Fig.11A is the complete inability of this observer to discriminate perceived speed during simulated forwards self-motion (open symbols) -- for all values of test target speed this observer perceived the reference target to be moving faster than the test target. Similar results were obtained for the other three observers. For all observers thresholds could not reliably be measured for the forward self-motion condition. Subjectively all observers reported only a very weak sensation of object MID during simulated forwards self-motion. Possible explanations for this effect are discussed below.

Results were substantially different for backwards self-motion (solid symbols). All four observers could reliably discriminate the speed of object MID and discrimination thresholds ranged from 6% to 15%. For backwards self-motion the PSE values were 0.54, 0.47, 0.51 and 0.44 for the four observers respectively. These values are all less than the speed of the reference target (0.56), thus the effect of backwards self-motion on speed judgments based on binocular information alone was to increase the perceived speed of MID. This effect is opposite to that found for judgments based on monocular information alone (Fig.3A). This result parallels our previous finding for TTC estimates for a stationary observer. TTC is underestimated when judgments are based on monocular information alone and overestimated when judgments are based on binocular information alone (Gray and Regan, 1998).

Monocular and Binocular Information Combined

Fig. 11B shows the psychometric functions for conditions in which object MID was produced by a combination of monocular and binocular information. Data are again for observer 1. Relative to the judgments based on binocular information alone (Fig.11A), speed discrimination performance for the forwards self-motion was dramatically improved when both MID cues were available. Discrimination thresholds in Fig.11B were 5.3% for forwards self-motion and 7.3% for backwards self-motion. Similar results were obtained for the other observers (thresholds ranged from 5% to 19% for forwards self-motion and 7% to 18% for backwards self-motion). Relative to the

judgments based on monocular information alone (Fig.2A), the effect of self-motion direction on the perceived speed of object MID was considerably reduced. Fig. 12 shows the PSE values for forwards and backwards self-motion for the 4 observers. For all observers, the pattern of results was the same as for monocular information alone (Fig.3A) although the effect size was reduced. A paired t-test revealed that the difference between the PSE values in the forwards vs. backwards conditions (i.e., the effect size) was significantly smaller for judgments based on a combination of binocular and monocular information than for judgment based on monocular information alone [$t(4)=7.5$, $p<0.001$].

Discussion

The addition of binocular information significantly reduced the effect of self-MID on the perceived speed of object MID. The improvement in performance produced by the addition of binocular information parallels our previous findings for judgments of TTC made by stationary observers (Gray & Regan, 1998). When only monocular TTC information was available observers consistently underestimated the TTC of a simulated approaching object (by 2% to 12%). However, when both monocular and binocular cues to TTC were available there was no consistent tendency to underestimate TTC and errors were small (ranging from 1.3 to 2.7%). As discussed below, our proposed explanation for the finding that performance is improved for combined cues is that binocular and monocular information about MID is combined in a weighted averaging process that takes into account the reliability of each source of information (Gray & Regan, 1998)).

An unexpected finding of Expt. 3 was that observers could not reliably discriminate object speed during simulated forwards self-motion when judgments were based on binocular information alone. It is has been well documented that the objects surrounding a target whose disparity is changing have a substantial effect on the sensation of motion of depth produced by the target. For example, in the complete absence of surrounding objects (i.e., so that the disparity change is absolute not relative), changing disparity produces (for small objects) only a weak sensation of motion in depth or (for large objects) no sensation at all (Regan, Erkelens & Collewijn, 1986). Furthermore, when surrounding objects are present the sensation of MID is strongest

when the surrounding objects are at exactly the same distance as the target (Regan & Beverley, 1973). In Expt. 3 all the flow elements surrounding the changing disparity target were moving, therefore it is possible that the absence of stationary reference marks degraded the sensation of MID in the present study. This explanation seems unlikely however, since the sensation of MID was not affected in the backwards self-motion condition that also had moving reference marks. We are unaware of any studies that have examined the effect of the motion of reference marks on the sensation of MID produced by changing disparity.

Experiment 4

In Expt.3 we found that the addition of binocular information about MID significantly reduced the interaction between object motion and self motion. The purpose of Expt.4 was to determine whether a similar effect would occur for judgments of the perceived direction of object MID.

The apparatus was as described in Expt.3 except that we varied the location of the focus of expansion (FOE) as described in Expt.2. We again used three different FOE locations: (a) 7 deg left of the center of the display (-7 deg), (b) center of the display (0 deg) and (c) 7 deg right of the center of the display (+7deg). In Expt.3, the direction of object MID was varied according to equation 4 (i.e., monocular information) and/or equation 5 (i.e., binocular information).

Psychometric functions for direction discrimination were measured as described for Expt. 2. The direction cues available to the observer were varied across runs. Each observer completed the following 3 conditions: (1) monocular information alone; (2) binocular information alone; (3) both monocular and binocular information signaling the same direction.

In order to check whether observers based their responses on the direction of the approaching object rather than on task–irrelevant variables such as frontal-plane speed or the rate of change of disparity, we used the triple dissociation technique described in Expt. 2. We also again collected data for a condition in which the flow elements remained static in both the reference and test intervals.

Four observers completed Expt. 1. Observer 1 was author R.G. The other three observers (observers 8, 9 and 10) were naïve to the aims of the study and completed the experiments for partial course credit.

Results and Discussion

Binocular Information Alone

Fig. 13A shows the psychometric functions for the condition in which the direction of object MID was signaled by binocular information alone (equation 5). Data are for observer 1. It is clear that direction discrimination performance was poor during simulated forwards self-motion. Direction discrimination thresholds for the three FOE locations were 11, 19 and 13 deg respectively. These thresholds are considerably higher than those found for monocular information alone in Expt.2 (6.6, 6.5, and 6.7 deg, see Fig.7) and are higher than that found for the 'static' condition of Expt.4 (mean threshold 3.8 deg). Similar results were obtained for the other three observers. A paired t-tests revealed that the mean direction discrimination threshold for estimates based on binocular information alone was significantly higher than for estimates based on monocular information alone [$t(4)=5.5$, $p<0.01$]. It is also clear from Fig.13A that there was no systematic effect of FOE location on the PSE (i.e., 50% point) when estimates were based on binocular information alone.

Monocular and Binocular Information Combined

Fig.13B shows psychometric functions for conditions in which the direction of object MID was signaled by a combination of monocular and binocular information. Data are again for observer 1. Relative to the judgments based on binocular information alone (Fig.13A), direction discrimination performance during forwards self-motion was dramatically improved when both MID cues were available. Direction discrimination thresholds in Fig.13B were 3.4, 2.9 and 3.7 deg for the FOE locations of –7, 0 and +7 deg respectively. Similar results were obtained for the other three observers. Relative to the judgments based on monocular information alone (Fig.7), the effect of self-motion direction on the perceived direction of object MID was considerably reduced [$t(4)=11.4$, $p<0.001$].

General Discussion

Crosstalk between the processing of object-motion and the processing of self-motion.

It has long been believed that humans and animals process the motion of objects in their environment independently of their own self-motion. For example, neurons in the tectofugal pathway of the pigeon are sensitive to various aspects of object-motion while effectively ignoring self-induced visual motion (Frost, Scilley & Wong, 1981). Conversely, neurons in the pigeon's accessory optic system are sensitive to elements of self-motion. A similar functional segregation of motion processing has been also found between areas MT and MST in monkeys (Duffy, 1998, Tanaka, Hikosaka, Saito, Yukie, Fukada & Iwai, 1986, Tanaka & Saito, 1989) and the temporooccipital and temporoparietal cortex in humans (Wiest, Amorim, Mayer, Schick, Deecke & Lang, 2001). At the behavioral level, the stimulus conditions which tend to produce the illusion of self-motion (i.e., movement of elements in peripheral vision that are perceived to be the background of the visual scene) are quite different from conditions which typically generate perceived object motion (i.e., movement of elements in central vision that are perceived to be the foreground of the visual scene) (Brandt, Koenig & Dichgans, 1973, Brandt, Wist & Dichgans, 1975). It has been proposed that this independence between processing of the two types of motion may be an effective strategy for solving the classical problem of distinguishing the motion of external objects from retinal image motion produced by a body, head or eye movement (Frost, Wylie & Wang, 1990).

However, we report here evidence that information about self motion and object motion are integrated in the perception of object movement in depth. In Expt. 1, the <u>perceived speed</u> of approaching are receding objects was altered by self-motion information (in particular, the angular speed and direction of the peripheral flow elements). In Expt. 2, the <u>perceived direction</u> of object MID was altered by self-motion information (in particular, the location of the focus of expansion of the flow field). Two points about these findings should be emphasized. First, these changes in perceived speed and direction occurred even though the peripheral flow field did not affect the local information about MID generated by the object itself (i.e., equations 1-5). Secondly, the observed changes in perceived speed and direction would seem to be maladaptive since

they would create inaccuracies in judging the future location of an approaching object under the everyday condition that the object's closing speed and trajectory is affected by self-motion.

In a series of papers Regan, Beverley, Hamstra and Gray have developed a model of the processing of MID and generation of estimates of TTC and speed (reviewed in Regan and Gray, 2000). In this model, the final MID signal for an approaching or receding object is generated from a weighted average of (i) signals from local relative motion (RM) filters that encode changes in the angular size of the entire object, (ii) signals from local RM filters that encode changes in the angular size of texture elements on the surface of the object, (iii) signals from local RM filters that encode changes in the separation between adjacent texture elements on the surface of the object, and (iv) filters that encode the object's rate of change of disparity relative to a fixed reference point. The findings of Expt. 1 indicate that self-motion signals from filters that encode the velocity of radial flow are also part of this weighted average. The data shown in Fig.5 suggest that this self-motion signal is based on all elements within roughly ±9 deg of the focus of expansion of the flow pattern. An expanding flow pattern would cause the object's closing speed to seem faster (and hence an underestimate of TTC); a contracting flow field would cause the object's closing speed to seem lower (and hence an overestimate of TTC). This model can also explain some of other findings we observed in the present study. For example, in Expt.3 the addition of binocular information significantly reduced the effect of self-motion on perceived speed. This effect can be explained in the model because binocular information accurately encodes the speed of MID so that the changing–disparity signal would partially offset the self-motion signal in the averaging process. The model can also explain the saturation effect shown in Fig.4A: as the speed of self-motion increases relative to the speed of object MID it will have a larger impact on the final weighted average until at some point the final MID speed will be effectively determined only by the self-motion signal. Finally, a prediction that comes from our model is that the effect of self-motion on the perceived speed of object MID should be larger for small objects because the signals from the RM filter that encode object expansion and the RM filters that encode texture element expansion are both smaller for small objects (Gray & Regan, 1998, 1999).

The interaction between self-motion and object-motion, and in particular the increase in MID detection thresholds caused by concomitant self-motion, has previously been explained in terms of a misdirected constancy mechanism (Probst et al., 1986), that is the internal signal (or 'efferent copy') used to cancel the retinal image motion of stationary objects during self-motion (von Holst & Mittelstadt, 1950) is somehow being misapplied to moving objects. However, this proposal cannot be used to generate quantitative predictions about the effect of different stimulus conditions on the interaction between self-motion and object-motion.

An adaptive interaction?

Why then does this interaction occur when it is seems to be maladaptive? We have previously suggested that the inaccuracies in object TTC perception produced by self-motion may in fact be ecologically advantageous (Gray & Regan, 2000b). Consider two cases of object interception: (i) a stationary observer reaching out to catch a ball and (ii) an observer running to catch a ball. It has previously been shown that binocular information acquired when the ball is within a few meters of the eyes is used to correctly time the finger flexions in catching (Alderson, Sully & Sully, 1974). Therefore, in case (i) it would be advantageous if the initial estimate of TTC based on monocular information were an underestimate because the unavoidable variability in the estimate will never create the situation where there is no time left to acquire the essential binocular information*. When the observer is in motion [case (ii)], the mass that must be controlled on the basis of close-range binocular information is much greater than in case (i). Thus, it would seem advantageous for the initial estimate of TTC to be an even larger underestimation during self-motion to allow the effects of body inertia to be overcome before binocular information becomes within the final few meters of the object's approach.

Implications for research on perception and action

---

* Several studies have shown that TTC is consistently underestimated when judgments are based on monocular information alone (equation 1) (reviewed in (Gray & Thornton, 2001)).

Almost all work on human object motion perception and all the animal experiments on object motion perception have involved a stationary observer and a real or simulated moving object (see (Nakayama, 1985; Regan, 1986; Regan & Gray, 2000 for reviews). On the face of it, this choice of methodology would seem to have general validity because the local optical information provided by the object itself (e.g., equations 1-5) provides accurate information about the trajectory and speed of the object motion regardless of whether the observer is stationary or moving. However, the results of the present study suggest that this large body of previous work has limited applicability to the more common situation where both the observer and the object are in motion: We find that the processing of object motion during self motion cannot in general be directly predicted from data obtained with a stationary observer.

Summary

Self–motion through a three–dimensional array of objects creates a radial flow pattern on the retina. We superimposed a simulated object moving in depth on such a flow pattern to investigate the effect of the flow pattern on judgements of both the time to collision (TTC) with an approaching object and the trajectory of that object. Our procedure allowed us to decouple the direction and speed of simulated self motion–in–depth (MID) from the direction and speed of simulated object MID. In Expt.1 we found that objects with the same closing speed were perceived to have a higher closing speed when self-motion and object motion were in the same direction and a lower closing speed when they were in opposite direction. This effect saturated rapidly as the ratio between the speeds of self-motion and object motion was increased. In Expt.2 we found that the perceived direction of object MID was shifted towards the focus of expansion of the flow pattern. In Expts.3 & 4 we found that the erroneous biases in perceived speed and direction produced by simulated self-motion were significantly reduced when binocular information about MID was added. These findings suggest that the large body of research that has studied motion perception using stationary observers has limited applicability to situations in which both the observer and the object are moving.

2.1(b). A potentially dangerous effect of adaptation to closing speed when turning across an approaching vehicle

Long Term Aim: 1.1.2; Specific Aim: 1.2.2, 1.2.7. This study has been published: Gray, R, Regan, D. Perceptual processes used by drivers during overtaking in a driving simulator. Human Factors, 47(2), 394-417.

We previously reported a new kind of adaptation to motion: closing speed adaptation (Gray & Regan, 1999). This effect is quite different from the well–known observation that adapting to the peripheral flow pattern caused by forward motion produces the illusion that one is traveling more slowly than the real speed. The effect is limited to ± 1 deg from the focus of expansion (Regan & Beverley, Science, 1979, 205, 311-313) and is caused by adaptation of looming detectors (Gray & Regan, Vision Research, 1999, 39, 3602-7) that specifically affects the perceived speed of closure onto an object rather than the perceived speed of self-motion. One practical consequence of the effect is that staring straight ahead while driving along a straight empty textured road causes a driver to perceive that the time to collision with a slowly moving vehicle is longer than it really is, and can produce dangerously late responses when overtaking or in collision avoidance (Gray & Regan, J. Expt. Psych. HPP, 2000, 1721-1732). *It seems likely that a similar effect can occur in NOE flight.*

We have now investigated whether adaptation to closing speed can cause potentially dangerous misjudgments when turning across an approaching vehicle as, for example, when taxiing an aircraft, or, in highway driving, when turning left across oncoming traffic. To anticipate, we find that the effect results in decisions that are delayed, higher risk, and more variable.

In a typical year (1996) 41, 907 were killed in highway accidents and 3.5 million injured within the USA alone (NHTSA, 1996). One of the more dangerous judgments a driver must make is whether there is sufficient time to complete a driving maneuver before colliding with an oncoming car, for example in overtaking, merging into traffic or executing a left-turn at an intersection. Previous experimental research and accident statistics have shown that drivers frequently make incorrect decisions in these situations (Jeffcoat, Skelton, Smeed, 1973; Clarke, Ward, Jones, 1998). For example, overtaking accidents account for nearly 10% of all fatal road accidents in

the English county of Nottinghamshire. Clarke et al. (Clarke, Ward, Jones, 1999) concluded that "the majority (of these accidents) arose from a decision to start the overtake in unsuitable circumstances" (p. 849). Similarly, in an analysis of accidents involving left-turns (which accounted for 17% of all accidents), Larsen & Kines (Larsen, Kines, 2002) concluded that "the main problems for left-turning drivers lay in their attention errors or in misjudging the time they had to make a left-turn before the approaching traffic reached the intersection" (pg. 375).

One reason for the high level of driver error involved in these situations is the complexity of the visual judgments involved (Hills, 1980). The driver must simultaneously estimate the time to collision (TTC) with an often distant oncoming car, monitor the lead car so as to avoid a rear-end collision (in overtaking), and estimate the time required to complete the desired maneuver based on the current speed, road conditions and knowledge of the capabilities of his/her own vehicle. These judgments are further complicated by the fact that a driver's estimates of speed and TTC can be distorted by factors such as fog (Snowden, Stimpson, Ruddle, 1998) and fatigue (Brown, Tickner, Simmonds, 1970). We have previously described the conditions that cause adaptation to closing speed, and have shown that this effect produces inaccurate estimates of TTC both in the laboratory (Gray & Regan, 1999) and in simulated driving (Gray & Regan, 2000) This effect is quite distinct from the well–known adaptation of the perceived speed of self motion that is caused by the expanding retinal flow pattern (Deonton, 1976), an effect that could not explain our driving simulator data (Gray & Regan, 2000). Here we ask whether the errors in estimating TTC caused by closing speed adaptation contributes to decision-making errors in these potentially dangerous driving situations.

We adapted participants to closing speed by having them drive straight ahead on a straight empty textured road for 5 min in a fixed-based driving simulator, and instructing them to gaze fixedly at the focus of expansion of the retinal flow pattern generated by the forward motion (Regan & Beverley, 1979). (The effect of closing speed adaptation on overtaking maneuvers is too dangerous to be studied in real-world driving). Participants were instructed to stay in the right lane and drive at any speed at or below the posted speed limit of 65mph (29 m/s). This Adaptation

Condition was compared to an Unadapted Baseline Condition in which participants sat in the car and stared straight ahead at a static view of the driving scene for 5 min. Participants began driving forward at the end of this static viewing period (signaled by an auditory tone). Further details of this procedure and the driving simulator can be found in Gray & Regan (2000). Each experimental trial consisted of the initial 5 min period followed immediately by one of four conditions: (1) Overtaking Maneuver, (2) Overtaking Judgment, (3) Left-Turn Execution, and (4) Left-Turn Judgment. All conditions used a simulated straight two-lane highway. During all driving maneuvers participants were instructed to always obey the speed limit. Specifics of the conditions were as follows:

Overtaking Maneuver. A lead-car (i.e., traveling in the same lane as the participant) appeared on the road ahead. Participants were instructed to adjust their speed so as to follow the lead car. After 5 sec of car following, a brief auditory tone was played and an oncoming car appeared on the roadway. Participants were instructed that when they heard the tone they should overtake and pass the lead vehicle when it was safe do so (i.e., either before or after the oncoming car had gone by). Following each overtaking maneuver participants drove for 656 ft (200m) on an empty road before approaching another lead vehicle to be followed and passed. Each trial consisted of 10 overtaking maneuvers. The speed of the lead car was varied randomly between 30 and 55 mph (13.4 to 24.6 m/s). The speed of the oncoming car was varied between 20 and 65mph (9 to 29 m/s).

Overtaking Judgment. This condition was identical to condition 1 except that, rather than executing the overtaking maneuver, participants made a passive judgment. After 5 sec of following the lead car, an oncoming car appeared on the roadway. A variable time after this car appeared an auditory tone was played. Participants were instructed that when they heard the tone they should press one of two response buttons on the steering wheel to indicate whether or not <u>at that instant</u> there would be sufficient time to pass before the oncoming car arrived. They were further instructed to respond as quickly as possible and response time was measured. After a response was received the other vehicles disappeared from the roadway and the participant

drove on a straight empty road for 656 ft (200m). Each trial consisted of 10 overtaking judgments.

Left-Turn Execution. Participants drove towards a 4-way intersection. An oncoming car approached the intersection at a variable speed [ranging between 30 and 65mph (13.4 to 29 m/s)]. The initial distance between the oncoming car and the intersection was varied between 80 and 200 ft (24 to 60m). Participants were instructed to turn left at the intersection when it was safe do so. Following each left turn participants drove on 656 ft (200m) of empty road before approaching another intersection. Each trial consisted of 10 left turns.

Left-Turn Judgment. This condition was the same as condition 3 except that participants were instructed to press one of two response buttons on the steering wheel immediately after hearing the auditory tone, the choice of button signaling whether a left-turn could be made safely before the approaching car reached the intersection. After a response was received the other vehicle and intersection disappeared from the roadway.

Eighteen participants completed all four conditions so there were 180 observations per condition. The calculation of the safety margin required for the overtaking maneuver is illustrated in Fig. 1A. We first calculated the distance required to overtake (DRO) based on the participant's current driving speed (S) using the equation

$$DRO = 112.2 + 15.2S + 0.093S^2 \quad \text{-----------} (8)$$

from the study of real driving by Gordon and Mast (Gordon, Mast, 1970). We then calculated the time required to overtake (TRO) using the participant's current driving speed and the simulated car's acceleration model. For this calculation we assumed that all drivers would pass the lead car at the maximum speed of 65mph (29 m/s). Finally, we calculated the time it would take the oncoming vehicle to reach the critical distance required to pass (TTCD) based on its speed and distance.

Fig. 14B shows the number of overtaking maneuvers that were initiated for different safety margins. Data are plotted as function of (TTCD-TRO) and are grouped into 0.9 sec ranges of this variable. For all values less than zero sec, an overtaking maneuver cannot be completed without a collision unless the participant

exceeds the speed limit or the oncoming vehicle decreases its speed. We defined this range to be unsafe. It is clear from this figure that the distribution of overtaking maneuvers was shifted rightward in the adaptation condition. Closing speed adaptation substantially increased the total number of unsafe overtaking maneuvers that were initiated as compared to the baseline condition (28 vs. 7). The mean (TTCD-TRO) at which overtaking was initiated was significantly lower in the adaptation condition [2.3(SE=1.9) sec] than in the baseline condition [3.5(SE=1.2) sec], thus creating a smaller margin for error for the overtaking maneuver [$t(17)=2.15$, $p<0.025$]. Similar results were obtained for the Overtaking Judgment condition. As compared to baseline condition, closing speed adaptation resulted in more 'yes it is safe to overtake' judgments (35 vs. 19) for unsafe values of (TTCD-TRO). Furthermore reaction times for these judgments were significantly slower [by 32 ms on average; $t(17)=1.8$, $p<0.05$] and had significantly larger variance [$F(17, 17)=3.5$, $p<0.01$] in the adaptation condition. This increase in reaction time and variability arises because adaptation greatly reduces the oncoming car's perceived rate of expansion (Regan & Beverley, 1979; Regan & Beverley, 1978), which is already small due to its small initial angular size. We have previously shown that the processing of motion in depth and TTC is degraded when an object's rate of expansion is near the detection threshold (Gray & Regan, 1998). The findings just described demonstrate that closing speed adaptation impaired the ability of our drivers to make the decision about whether it was safe to initiate an overtaking maneuver.

The calculation of the safety margin required for execution of a left-turn is illustrated in Fig.15A. In order to determine the time required to turn (TRT) as a function of the approach speed we conducted a pilot study where five drivers executed left-turns for a range of approach speeds. In this pilot study we found that the TRT (calculated from the point when the steering wheel began to turn) was roughly constant for different approach speeds, because our drivers always decelerated to a roughly constant speed before initiating the turn. To determine the safety margin, the TRT value was compared to the time required for the oncoming to reach the intersection (TTI) that was calculated from its speed and distance.

Fig 15B show the number of left-turns that were initiated for different ranges of (TTI-TRT). Again values of (TTI-TRT) less than zero were defined to be unsafe, because the oncoming car would have reached the intersection before the left-turn was completed. The effect of closing speed adaptation on left-turn execution was similar to the effect on overtaking described above: drivers made more unsafe turns (47 vs. 13) and the mean (TTI-TRT) value at left-turn initiation was significantly lower in the adaptation condition [0.7(SE=1.7) sec] than in the baseline condition [2.05(SE=1.2) sec]; [$t(17)=3.8$, $p<0.01$]. Adaptation again had the effect of significantly reducing the driver's safety margin. In the left-turn judgment condition drivers made more unsafe judgments following adaptation (62 vs. 23) compared to baseline and reaction time were significantly slower [by 20 ms on average, $t(17)=1.77$, $p<0.05$] .

Adaptation to closing speed can occur when a driver gazes fixedly at the road or at an oncoming vehicle rather than scanning the scene ahead (Regan & Beverley, 1979). Our driving simulator results suggest that, in real-world driving situations, closing speed adaptation may impair the ability of a driver to decide accurately whether they have sufficient time to complete a maneuver such as an overtake or a left-turn while avoiding collision with an oncoming car. Closing speed adaptation not only makes judgments slower but also substantially biases the driver towards an underestimate of the time required, thus increasing the probability of collision.

Summary

Drivers are often faced with decisions, which have potentially life-threatening consequences. Accident reports indicate that errors in decision-making during driving (e.g., deciding whether or not to pull out in front of another vehicle) are the probable cause of the majority of accidents on our roadways. One possible source of these errors of judgment is that in some situations the information provided by the human visual system is inaccurate. We have previously shown that staring straight ahead during simulated driving on a straight open road can give the driver the illusion that the time to collision with other vehicles is longer than it really is. This effect occurs because the neural mechanisms in the human visual system sensitive to time to

collision with an approaching vehicle become adapted to closing speed. Here we show that this closing speed aftereffect can impair the ability of a driver to decide whether there is sufficient time to (i) overtake another vehicle on the highway and (ii) execute a left-turn in front of oncoming traffic. Closing speed adaptation resulted in decisions that were delayed, of higher risk, and more variable.

2.2 Visual Psychophysics

2.2(a) Evidence that practice can change the interaction between different visual variables in visually-guided action

Our evidence so far indicates that, for a specific visually–guided action, practice can alter the visuo–motor system so as to improve the performance of that specific action.

We used our previously–developed method (Regan & Hamstra, *Vision Research*, 1993, 33, 447-462; Portfors–Yeomans & Regan, *J.Exp. Psychol, HPP*, 1997, 23, 227-243; Gray & Regan, *Vision Research*, 1998, 38, 499-512.) to quantify the degree to which an observer's responses were influenced by visual variables other than the task–relevant variable. We simulated a rotating textured baseball approaching along a straight line, and required observers to judge the direction of motion in depth, the time to passage, and the rate of rotation after each stimulus presentation. A group of observers who did not play baseball based all three judgements almost entirely on the task–relevant variable while ignoring task–irrelevant variables. Results were different for a group of expert baseball players. Ball rotation affected their predictions of the time of arrival of the ball.

The force of this point is that, because of the biomechanics of pitching in baseball, a fastball has a component of backspin and a slower curveball has a component of overspin. Only expert batters face pitchers capable of accurately throwing a fastball or a curveball. And it has been shown that expert baseball players can use the direction of spin to help time the swing, while novices do not have that ability.

In a previous study on highly–skilled pilots flying telemetry–tracked jet aircraft, we reported that inter-individual differences in the performance of some flying tasks showed moderate correlations with the independence of processing of changing–size

(motion in depth) and frontal plane motion (Kruk & Regan, *Aviation, Space & Environ. Medicine,* 1983, 54, 906-911). This finding brings out the point that, while a correlation between visual variables (in baseball, a trajectory with overspin versus underspin) can render a learned dependence of processing advantageous within a highly–constrained situation, in less constrained situations it is processing independence that is advantageous.

Data collection is, we think, now complete and we are processing the data and working on a report for publication.

2.2(b) Early visual processing of time to collision and time to passage: a review

Long Term Aims 1.1.1, 1.1.2; Specific Aim 1.2.2, 1.2.4.

Regan, D & Gray, R (2003). A step–by–step approach to research on time–to–contact and time–to–passage. In "Time to Contact" (Eds. H. Hecht & G.J.P.Savelsberg) Amsterdam: Elsevier, pp. 174–228.

The relevance of this review is as follows: collision avoidance; the design of binocular and monocular flight simulators and, in particular, the effectiveness of training in collision avoidance.

This is a detailed critical review, incorporating considerable new material and theoretical work, and pointing out several major and misleading errors in published work on the topic.

2.2(c) The early visual processing of binocular information about time to collision: a review.

Long Term Aims 1.1.1, 1.1.2; Specific Aim 1.2.2, 1.2.4.

Gray, R. & Regan, D (2003). Binocular information about time to collision. In "Time to Contact" (Eds. H. Hecht & G.J.P.Savelsberg) Amsterdam: Elsevier, pp. 229–240.

Relevance as for 2.2(a).

2.2(d) Absolute accuracy in judging the direction of motion in depth: a comparison of perception and action.

Long Term Aims 1.1.2; Specific Aim 1.2.7.

We quantified the accuracy of the perception of the absolute direction of motion in depth (MID) of a simulated approaching object using a passive judgement and an active simulated catching task. I n contrast with previous research, our passive judgement task utilized a staircase tracking procedure that provided precise estimates of the perceived direction of MID and did not require the observer to make an interceptive motor response. For the active task, movements of the index finger and thumb of the observer's hand were tracked as participants tried to 'catch' the simulated approaching object. A sensation of MID was created using monocular and/or binocular information sources and visual stimuli were identical for both tasks. For the judgement task, observers overestimated the angular trajectory of the approaching object, i.e. they judged the object to pass wider than the head than indicated by the visual information provided. When auditory feedback was added to the judgement task consistent overestimates were still observed. For the active task, observers consistently overreached i.e., the hand was further away from the midline than the simulated object at the time of hand closure. When auditory feedback was added to the active task errors were significantly reduced and were within the margin of error for successful catching. The relative accuracy in binocular and monocular conditions for individual observers could be partially explained by thresholds for unidirectional changes in angular size and changes in relative disparity. These findings suggest that adaptation of the motor component to the information provided by the visual system is the basis of successful interception. These findings are in press in *Vision Research.*

2.3 Evoked potential studies.

2.3(a). Distinction between brain responses to spatial form, disparity and motion.

Long term aim 1.1.3; Specific Aim 1.2.18.

The appearance and disappearance of a cyclopean form are both necessarily accompanied by a change in the relative disparities of the texture elements in some

part(s) of the dynamic random noise display. In electrophysiological studies this causes a problem in distinguishing between response to (1) the appearance and disappearance of cyclopean spatial form and (2) the associated changes in local disparity. There is a similar problem in distinguishing between responses to (1) the appearance and disappearance of motion–defined spatial form and (2) the associated changes in local motion.

We have developed a method for dissociating these responses and de–bugged the software.

2.3(b) Review articles on evoked potentials.

Four review articles are listed in Section 5.2 (numbers 5, 6, 7 and 9)

3. REFERENCES FOR ACCOMPLISHMENTS / NEW FINDINGS SECTION.

Alderson, G.J.K., Sully, D.J., & Sully, H. (1974). An operational analysis of a one-handed catching task using high-speed photography. *Journal of Motor Behavior, 6, 217-226.*

Beverley, K.I., & Regan, D. (1973). Evidence for the existence of neural mechanisms selectively sensitive to the direction of movement in space. *J Physiol* 235, 17–29.

Beverley, K.I., & Regan, D. (1975). The relation between discrimination and sensitivity in the perception of motion in depth. *J Physiol*, 249 (2), 387-398.

Bootsma, R.J. (1991). Predictive information and the control of action: what you see is what you get. *International Journal of Sports Psychology*, 22, 271-278.

Brandt, T., Koenig, E., & Dichgans, J. (1973). Differential Effects of Central Versus Peripheral Vision on Egocentric and Exocentric Motion Perception. *Experimental Brain Research*, 16 (5), 476-491.

Brandt, T., Wist, E.R., & Dichgans, J. (1975). Foreground and Background in Dynamic Spatial Orientation. *Perception & Psychophysics*, 17 (5), 497-503.

Brown, I. D., Tickner, A. H. & Simmonds, D. C. V. Effect of prolonged driving on overtaking criteria. *Ergonomics* 13, 239-242 (1970).

Clarke, D. D., Ward, P. J. & Jones, J. Overtaking road-accidents: differences in maneuver as a function of driver age. *Accid Anal Prev* 30, 455-67 (1998).

Clarke, D. D., Ward, P. J. & Jones, J. Processes and countermeasures in overtaking road accidents. *Ergonomics* 42, 846-867. (1999).

Denton, G. G. The influence of adaptation on subjective velocity for an observer in simulated rectilinear motion. *Ergonomics* 19, 409-30 (1976).

Duffy, C.J. (1998). MST neurons respond to optic flow and translational movement. J Neurophysiol, 80 (4), 1816-1827.

Finney, D.J. (1971). *Probit Analysis.* (Cambridge: Cambridge University Press.

Frost, B.J., Scilley, P.L., & Wong, S.C.P. (1981). Moving Background Patterns Reveal Double-Opponency of Directionally Specific Pigeon Tectal Neurons. *Experimental Brain Research,* 43 (2), 173-185.

Frost, B.J., Wylie, D.R., & Wang, Y.C. (1990). The Processing of Object and Self-Motion in the Tectofugal and Accessory Optic Pathways of Birds. *Vision Research,* 30 (11), 1677-1688.

Gordon, D. A. & Mast, T. M. Driver's judgments in overtaking and passing. *Human Factors* 12, 341-346 (1970).

Gray, R. & Regan, D. Accuracy of estimating time to collision using binocular and monocular information. *Vision Research* 38, 499-512 (1998).

Gray, R. & Regan, D. Adapting to expansion increases perceived time-to-collision. *Vision Research* 39, 3602-7 (1999).

Gray, R. & Regan, D. Risky driving behavior: a consequence of motion adaptation for visually guided motor action. *J Exp Psychol Hum Percept Perform* 26, 1721-32 (2000).

Gray, R., & Regan, D. (1998). Accuracy of estimating time to collision using binocular and monocular information. *Vision Research,* 38 (4), 499-512.

Gray, R., & Regan, D. (1999). Motion in depth: adequate and inadequate simulation. *Percept Psychophys,* 61 (2), 236-245.

Gray, R., & Regan, D. (2000a). Estimating the time to collision with a rotating nonspherical object. *Vision Research,* 40 (1), 49-63.

Gray, R., & Regan, D. (2000b). Simulated self-motion alters perceived time to collision. *Curr Biol*, 10 (10), 587-590.

Gray, R., & Thornton, I.M. (2001). Exploring the link between time to collision and representational momentum. *Perception*, 30 (8), 1007-1022.

Gray, R., Macuga, K. 7 Regan, D (2004). Long range interactions between object–motion and self–motion in the perception of motion in depth. *Vision Research* 44, 179–195.

Hills, B. L. Vision, visibility, and perception in driving. Perception 9, 183-216 (1980).

Hoyle, F. (1957). *The Black Cloud.* Middlesex, England: Penguin.

Jeffcoat, G. O., Skelton, N. & Smeed, R. J. (University of London, International Driver Behavior Research Association, London, 1973).

Keppel, K. (1991). *Design and Analysis*: A Researcher's Handbook. (Englewood Cliffs: Prentice Hall.

Larsen, L. & Kines, P. Multidisciplinary in-depth investigations of head-on and left- turn road collisions. *Accident Analysis and Prevention* 34, 367-380 (2002).

Lee, D.N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, 5 (4), 437-459.

Nakayama, K. (1985). Biological image motion processing: a review. *Vision Research,* 25 (5), 625-660.

Newell, K.M. (1974). Decision Processes of Baseball Batters. *Human Factors*, 16 (5), 520-527.

NHTSA. (National Highway Traffic Safety Administration, Washington, D.C., 1996).

Portfors-Yeomans, C.V., & Regan, D. (1997). Discrimination of the direction and speed of motion in depth of a monocularly visible target from binocular information alone. *J Exp Psychol Hum Percept Perform*, 23 (1), 227-243.

Probst, T., Brandt, T., & Degner, D. (1986). Object-motion detection affected by concurrent self-motion perception: Psychophysics of a new phenomenon. *Behavioral Brain Research*, 22, 1-11.

Regan, D. & Beverley, K. I. Looming detectors in the human visual pathway. *Vision Rees* 18, 415-21 (1978).

Regan, D. & Beverley, K. I. Visually guided locomotion: psychophysical evidence for a neural mechanism sensitive to flow patterns. *Science* 205, 311-3 (1979).

Regan, D. (1986). Visual processing of four kinds of relative motion. *Vision Research,* 26 (1), 127-145.

Regan, D. (1993). Binocular correlates of the direction of motion in depth. *Vision Research,* 33 (16), 2359-2360.

Regan, D. (1995). Spatial orientation in aviation: visual contributions. *J Vestib Rees,* 5 (6), 455-471.

Regan, D. (2002). Binocular information about time to collision and time to passage. *Vision Research,* in press.

Regan, D.(2002). Binocular information about time to collision and time to passage. *Vision Research,* 2479-2484.

Regan, D., & Beverley, K.I. (1973). Some dynamic features of depth perception. *Vision Research*, 13, 2369-2379.

Regan, D., & Beverley, K.I. (1979). Visually guided locomotion: psychophysical evidence for a neural mechanism sensitive to flow patterns. *Science*, 205 (4403), 311-313.

Regan, D., & Beverley, K.I. (1980). Visual responses to changing size and to sideways motion for different directions of motion in depth; linearization of visual responses. *J. Opt. Soc. Amer.*, 11, 1289–96.

Regan, D., & Gray, R. (2000). Visually guided collision avoidance and collision achievement. *Trends in Cognitive Sciences*, 4 (3), 99-107.

Regan, D., & Hamstra, S.J. (1993). Dissociation of discrimination thresholds for time to contact and for rate of angular expansion. *Vision Research,* 33 (4), 447-462.

Regan, D., & Kaushal, S. (1994). Monocular discrimination of the direction of motion in depth. *Vision Research,* 34 (2), 163-177.

Regan, D., Erkelens, C.J., & Collewijn, H. (1986). Necessary conditions for the perception of motion in depth. *Invest Ophthalmol Vis Sci*, 27 (4), 584-597.

Regan, D., Hamstra, S.J., Kaushal, S., Vincent, A., Gray, R., & Beverley, K.I., (1995). Visual processing of the motion of an object in three dimensions for a stationary or a moving observer. *Perception*, 24, 87–103.

Royden, C.S., & Hildreth, E.C. (1996). Human heading judgments in the presence of moving objects. *Perception & Psychophysics*, 58, 836-856.

Snowden, R. J., Stimpson, N. & Ruddle, R. A. Speed perception fogs up as visibility drops. *Nature* 392, 450 (1998).

Szirtes, T. (1998). *Applied Dimensional Analysis and Modeling*. New York: McGraw–Hill.

Tanaka, K., & Saito, H. (1989). Analysis of motion of the visual field by direction, expansion/contraction, and rotation cells clustered in the dorsal part of the medial superior temporal area of the macaque monkey. *J Neurophysiol*, 62 (3), 626-641.

Tanaka, K., Hikosaka, K., Saito, H., Yukie, M., Fukada, Y., & Iwai, E. (1986). Analysis of local and wide-field movements in the superior temporal visual areas of the macaque monkey. J Neurosci, 6 (1), 134-144.

von Holst, E., & Mittelstadt, H. (1950). Das Reafferenzprincip. *Naturwissenschaften*, 37, 464-476.

Wann, J.P. (1996). Anticipating arrival: is the tau margin a specious theory? J Exp *Psychol Hum Percept Perform*, 22 (4), 1031-1048.

Warren, W.H., Jr., & Saunders, J.A. (1995). Perceiving heading in the presence of moving objects. *Perception*, 24 (3), 315-331.

Wiest, G., Amorim, M.A., Mayer, D., Schick, S., Deecke, L., & Lang, W. (2001). Cortical responses to object-motion and visually-induced self- motion perception. *Cognitive Brain Research*, 12 (1), 167-170.

4. PERSONNEL SUPPORTED

<u>Professional personnel supported by / or associated with the research effort</u>

Prof. D. Regan

Dr. Marian P. Regan

Dr. X.H. Hong

Prof. R. Gray

5. PUBLISHED DURING THE GRANT PERIOD

5.1 Papers in peer–reviewed journals

(1) Gray R, Macuga C, Regan D (2004). Long range interactions between object–motion and self–motion in the perception of movement in depth. *Vision Research*, 44, 179-195.

(2) Gray R, Regan D (2005). Perceptual processes used by drivers overtaking in a driving simulator. *Human Factors*, 47(2), 394-417.

(3) Gray R, Regan D (2005). Unconfounding the time to passage direction of motion, and rotation rate of an approaching object: different early visual processing in expert baseball players and nonplayers. *Vision Research*, in press.

5.2 Book Chapters

(4) Regan D (2003). Early processing of spatial form. In *Adler's Physiology of the Eye*. (Eds. P.L. Kaufman & A. Alm), pp. 470-483.

(5) Regan D, Regan MP (2005). The processing of spatial form by the human brain studied by recording the brain's electrical and magnetic responses to visual stimuli. In Harris L & Jenkin M (eds.). *Visual Processing of spatial form*. Cambridge Univ. Press, in press.

(6) Regan D (2003). Evoked potentials, visual human. In *Encyclopedia of Neuroscience*, Elsevier.

(7) Regan D, Regan MP (2003). Evoked potentials, recording methods. In *Encyclopedia of Neuroscience*, Elsevier.

(8) Regan D, Gray R (2003). A step by step approach to research on time–to–contact and time–to–passage. In *Time to Contact* (Eds. H. Hecht, G.J.P. Savelsburg). Amsterdam: Elsevier, pp. 174-228.

(9) Regan MP, Regan D (2003). Techniques for investigating and exploiting nonlinearities in brain responses evoked by sensory stimuli. In Z.L. Lu, G.

Sperling & L. Kaufman (Eds.). *Magnetic source imaging of the human brain.* Erlbaum: Mahwah, N.J. pp. 135–157.

6. INTERACTIONS / TRANSITIONS

6(a) Presentations at meetings, seminars etc.

(1) Regan, D: *Long–distance interactions in spatial vision.* International conference: Festschrift for D. Regan, York University, June 2003.

(2) Regan, D: *Visual psychophysics in ophthalmology and neurology.* International conference: Festschrift for D. Regan, York University, June 2003

(3) Regan, D: *Visual evoked potentials.* Festschrift for Henk Spekreijse, Amsterdam, October 2003.

(4) Regan, D: *Visually–guided collision avoidance and collision achievement in aviation, highway driving and sport.* Purdue University, November 2003.

(5) Gray, R., Castaneda, B., Sieffert, R. & Regan, D. *Comparing the relative accuracy of perception and action in ball catching.* VSS annual meeting. Sarasota, May 2005.

(6) Regan, D. *Psychophysical research on multiple sclerosis 1970–.* International workshop on medical applications of vision research, York University, July 2005.

6(b) Editorial Board: *Spatial Vision*

Editorial Board: *Ophthalmic and Physiological Optics*

7. HONORS / AWARDS

7.1. Awards during the grant period

In June 2003 the Canadian psychological Association awarded the P.I. the Hebb Award, their highest honor.

7.2. Lifetime achievement honors prior to grant period.

Queen Elizabeth II gold medal, August 2002.

Member of the Order of Canada (for contributions to science, medicine, and highway safety), July 2001.

Proctor medal for 2001, Senior award of the Association for Research in Vision and Ophthalmology, June 2000.

NSERC Award of Excellence, October 2000.

Elected Foreign Fellow of the Netherlands Royal Academy of Science, 1999.

Elected Spinoza Chair for 1999 by the medical faculty of the University of Amsterdam and gave the 5 Spinoza lectures.

Sir John William Dawson Medal, highest award of the Royal Society of Canada, 1997.

Charles F. Prentice Medal, highest award of the American Academy of Optometry, 1990

Fellow of the Royal Society of Canada, 1989

D.Sc. (London University, 1974)

Distinguished Research Professor, York University, 1991

I.W. Killam Fellow, 1991

I.W. Killam Research Professor, 1978

Medical Research Council of Canada Lecture, 1990

Max Forman Prize for Medical Research

Fellow of the Optical Society of America

Fellow of the American Academy of Optometry

Fellow of the Canadian Psychological Association

Listed in "Who's Who in America" ,"Canadian Who's Who" ,"American Men & Women of Science, "International Who's Who in Medicine", "Who's Who in Engineering", "Dictionary of International Biography"